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INVESTIGATION OF A LASER ILLUMINATOR - THERMAL IMAGING SYSTEM FOR THE DETECTION OF VOIDS AND DISBONDS

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by OTTO RENIUS

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INVESTIGATION OF A LASER ILLUMINATOR - THERMAL IMAGING SYSTEM FOR THE DETECTION OF VOIDS AND DISBONDS

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ABSTRACT

An infrared nondestructive testing technique employing laser heating of the specimen was developed and evaluated on several bonded materials. Thermal images were obtained using a two-dimensional reflective scanner coupled to a 30-watt CO_2 laser to irradiate the specimen and a thermal imaging camera to view the specimens irradiated surface. The technique is capable of providing a versatile, high-resolution, real-time nondestructive test for subsurface defects in large specimens.

Figure Number

INTRODUCTION

The use of infrared imaging devices for nondestructive testing has expanded rapidly due in part to the advances in military infrared technology. Highly sensitive detectors and complex scanners were developed for military use. As security restrictions were lifted, high resolution thermal cameras were built for commercial applications. Today both the industrial and medical fields, as well as the military, make wide use of infrared in a variety of tests.

As contrasted with radiometry which presents a graphical or digital output of the detector response, a thermal imaging camera allows the construction of a picture of an object which gives a visual presentation of variations in heat emitted by the area under scrutiny. Thus, any malfunction or defect which causes a sufficiently large variation in the surface temperature of an object can be detected by infrared imagery.

Thermal imaging techniques of nondestructive testing rely on the contrast in radiation between components or sections of a component to indicate the presence of defects and malfunctions. To achieve this contrast, various methods have been devised for heating the specimen in order to obtain sufficient infrared emission for thermal imagery. Most of these techniques result in excessive heating times or require close proximity between the specimen and heat source.

Infrared nondestructive testing techniques can be divided into two broad categories, active and passive, as in military infrared applications. In the passive mode, the entire specimen itself is the source of radiation. It may be in a transition between two temperature levels, either heating up or cooling down to the background equilibrium. In the active method, heat is selectively injected into a specimen at or near ambient temperatures. Detectable differences in heat transfer through the specimen are then used to indicate the presence of voids of defects.

Preliminary calculations were performed to determine the feasibility of employing active infrared methods to make the examination of large specimens more practical. This approach had been taken by several investigators to study small specimens with radiometric instrumentation, and had achieved limited success using resistance heaters as the active source.[1,2] This task investigated the use of a two-dimensional reflective scanner coupled to a 30-watt CO_2 laser to irradiate the specimen and a modified AGA three-channel infrared camera to view the specimen's irradiated surface. The system is capable of providing a high resolution real-time nondestructive test for subsurface defects.

RECOMMENDATIONS

It is recommended that the laser illumination - thermal imaging technique for nondestructive testing be applied to materials testing problems involving the detection of near-surface voids and disbonds. To increase the versatility of the technique, further work should be devoted to the refinement of the two-dimensional scanner equipment to more readily alter the size of the area scanned, scanning speed, and distance between scanning lines.

SUMMARY

The development of a two-dimensional long wave-length laser scanner for use in conjunction with thermal imagery expands the application of infrared nondestructive testing techniques. This is especially evident in the potential application to relatively large specimens since the low atmospheric absorption of the 10.6 micron laser beam [3] allows a long scanning path to be used without serious degradation of the beam intensity.

From the results obtained under laboratory conditions, it can be concluded that laser illumination - thermal imagery can be used as a nondestructive testing technique for a variety of bonded specimens. The technique is particularly useful for the examination of specimens that have a thin cross section or where the distance from the outer surface to the bond area does not exceed 1/4 inch. The potential usefulness of laser heating of thick specimens is limited to the evaluation of flat specimens having shallow sub-surface voids. The technique, therefore, should not be considered as a method for the evaluation of track pad or road wheel metal-rubber bonds.

TECHNICAL CONSIDERATIONS

All matter continuously absorbs and emits electromagnetic radiation. The continual motion of the charged particles within a material result in this emission. Since the thermal motion increases with temperature, the continuous radiation from the material also increases with temperature. The theory of this radiation is given by Planck's equation which expresses the relationship between E_λ and λ

$$E_\lambda = \frac{2\pi c^2 h}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

When the limits $\lambda = 0$ to $\lambda = \infty$ are considered Planck's equation yields the Stephan-Boltzmann Law $e_B = \sigma T^4$ where σ is the Stephan-Boltzmann constant $= 5.735 \times 10^{-8}$ watts/ M^2 - deg ^{4}. This law states that the total energy radiated by a perfect black body is proportional to the fourth power of the absolute temperature. The ratio of the total emissive power of any body to that of a perfect black body at the same temperature is called the emissivity (e) and is numerically equal to the absorptivity of the body.

When radiant energy from the CO_2 laser falls upon the specimen, part is absorbed and part is reflected. Assuming a uniform specimen surface, the amount of total incident radiation absorbed by the specimen due to the continuously scanning laser beam is equal for the entire surface. The result is an increase in surface temperature and a flow of heat through the specimen. For a homogeneous sample, the quantity of heat that will flow by conduction per unit of time is proportional to the thermal conductivity of the material, and the irradiated surface temperature will decrease uniformly after the laser beam has passed.

If, however, voids exist in the specimen, the thermal conductivity is altered, with a resulting alteration in surface temperature in the area of non-homogeneity. This non-homogeneity can then be detected by a radiometer or thermal imaging device if it causes surface temperature variations sufficiently large to fall within the sensitivity range of the instrument.

APPROACH

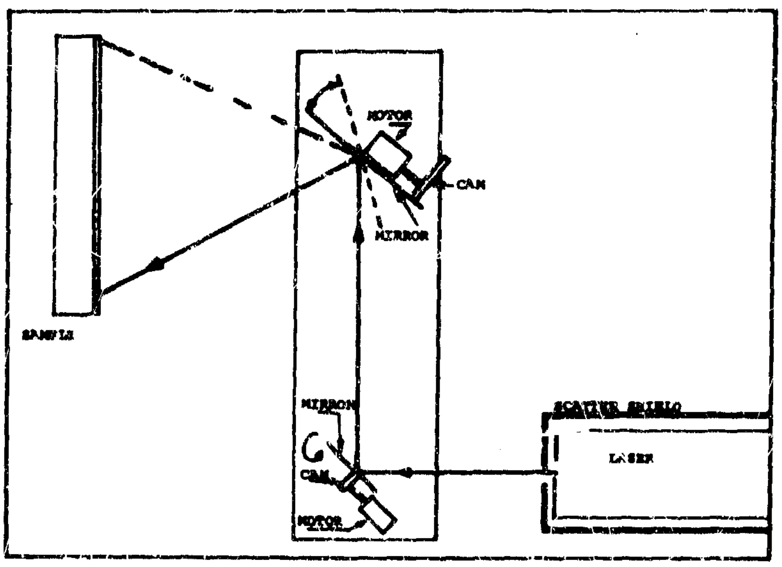
Since a laser is capable of imparting a large amount of thermal energy to a small surface area, it becomes a convenient method of quickly raising the specimen's surface temperature. A continuous wave CO_2 laser was tentatively selected as the source because it is readily obtainable with sufficiently high output to be useful. In addition, the output (10.6 Microns) cannot be detected by the thermal imaging camera which has a long wavelength cutoff of 5.4 microns. The infrared camera then sees only the energy re-radiated by the specimen and is "blind" to any portion of the laser beam scattered by the specimen or other reflecting surfaces. The disadvantage of using the CO_2 laser as the energy source is the difficulty in locating and aligning the invisible beam.

Two approaches were considered for expanding the 1/4 inch diameter laser beam to cover the total specimen area. The first, use of a wobbling, cassegrain reflective optical system to expand the beam, was discarded in favor of a reflective two-dimensional scanning system which would provide a rectangular scanning pattern.

EQUIPMENT DESCRIPTION

Reflective mirrors were prepared for positioning in front of the laser to provide the two-dimensional scan. Mirrors were fabricated from aluminum on pyrex, gold on pyrex, and stannous chloride on pyrex. Freshly deposited aluminum on pyrex proved to be the best reflector for the laser beam.

Motor driven cams were used to achieve a two-dimensional scanning pattern. Figure 1 is the diagram of the scanner which was fabricated.



ARRANGEMENT OF TWO DIMENSIONAL SCANNER

FIGURE 1

After the beam emerges from the shielded laser source, it strikes the first mirror and is reflected. This mirror is pivoted so that it can be tilted in the vertical direction when driven by a cam. The reflected beam strikes the second

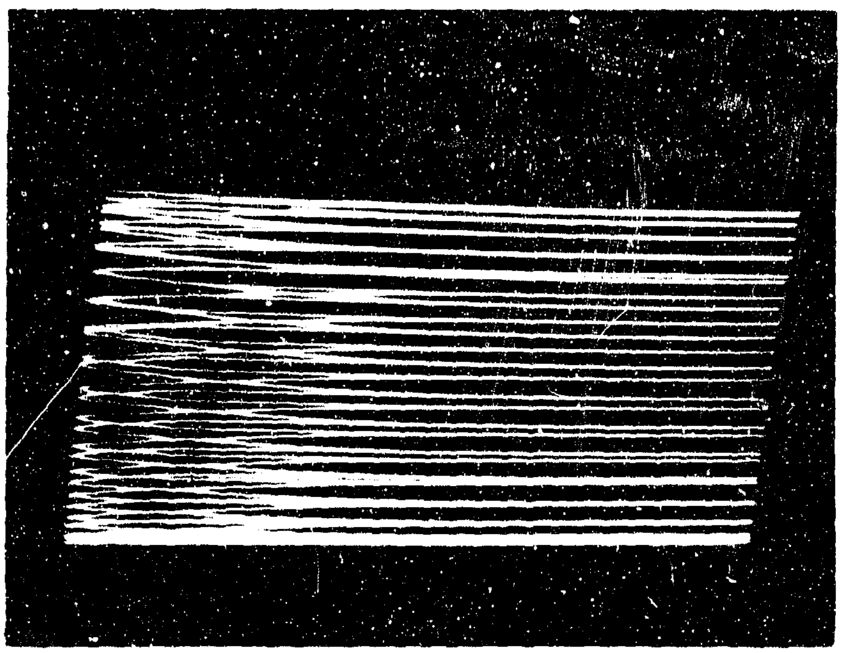
mirror which rocks back and forth, reflecting the laser beam in a horizontal line. At the end of each oscillation, the mirror depresses a microswitch which activates the cam driving the first mirror causing it to tilt slightly in the vertical direction. A two-dimensional scanning pattern is thus reflected onto the specimen's surface.

Figure 2 illustrates the scanner mounted in front of a neon-helium laser to check the mirror alignment. It was necessary to employ a relatively low power laser which emitted visible light for this purpose. After acceptable alignment was achieved, all mirrors were securely fastened to the mounting frame.

TWO DIMENSIONAL SCANNER WITH NEON-HELIUM LASER

FIGURE 2

Figure 3 illustrates the pattern which was obtained when the scanner was operated in front of a neon-helium laser. The area covered by this scan was 9 inches X 18 inches. For the remainder of the studies, the scanner was positioned in front of the 30 watt CO_2 laser.



SCANNING PATTERN OF LASER BEAM

FIGURE 3

Thermal images of the specimens were obtained with a three-channel infrared camera modified such that the energy from the specimen is displayed in three different optical regions. The three optical bandpasses are: 2.0 to 5.4 micron, 3.6 to 4.4 micron and 4.35 to 5.15 micron. A description of the camera is given in the following summary of data:

Range of focus	Two meters to infinity
Field of view	5° X 5° (1 m X 1 m at 10 meters)
Number of lines per frame	100
Frame rate	16 per second
Optical resolution	About 100 elements per line
Thermal discrimination	Two black body areas at room temperature can be separated if their temperature difference is larger than 0.2°C.
Picture temperature range (black to white)	Maximum 200°C Minimimum 1°C
Object temperature level	-30°C to +200°C
Isotherm width	From 1% to 30% of the selected temperature range
Detector type	Indium antimonide cooled by liquid nitrogen. Detector dewar holds 100 cc, sufficient for four hours.

SPECIMENS

A laminated plate with built-in defects was used as the primary specimen for evaluating the laser-thermal imaging system. This specimen consisted of a 1/8 inch rubber sheet bonded to an one inch thick aluminum backing plate. Two voids were machined into the aluminum plate prior to cementing the rubber to the surface. Each void was 7/8 inch diameter. One void was machined 1/8 inch into the plate and the other was machined 1/2 inch deep.

Other specimens were prepared from bonded sheet metal, a section of foamed-in-place polyurethane between two panels of 1/4 inch fiberglass, and from tank track pads. A 3/8 inch diameter void was drilled in the fiberglass specimen to provide the defect. The track pads had known separations which were located by radiographic examination prior to thermographic evaluations. The bonded sheet metal specimen is described in the section "Results".

EXPERIMENTAL PROCEDURE

A heat penetrameter was fabricated to insure that the infrared camera focus was optimum under all experimental conditions. This penetrameter consisted of a thin sheet of molybdenum spaced 1 inch in front of an aluminum plate. Three holes were spaced in the molybdenum. The holes were 1/4 inch, 3/8 inch, and 1/2 inch diameter. The molybdenum sheet was then resistance-heated to a temperature slightly above ambient and viewed with the thermal imaging camera. Focus was adjusted for a maximum resolution of the three holes. The 1/4 inch hole was visible only when the instrument was properly focused and adjusted. Figure 4 is a thermal image of the heat penetrameter with the three holes visible.

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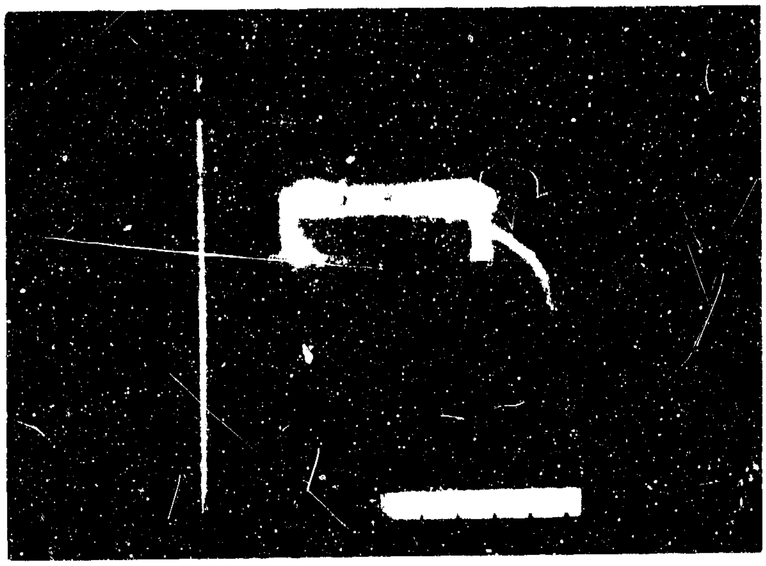
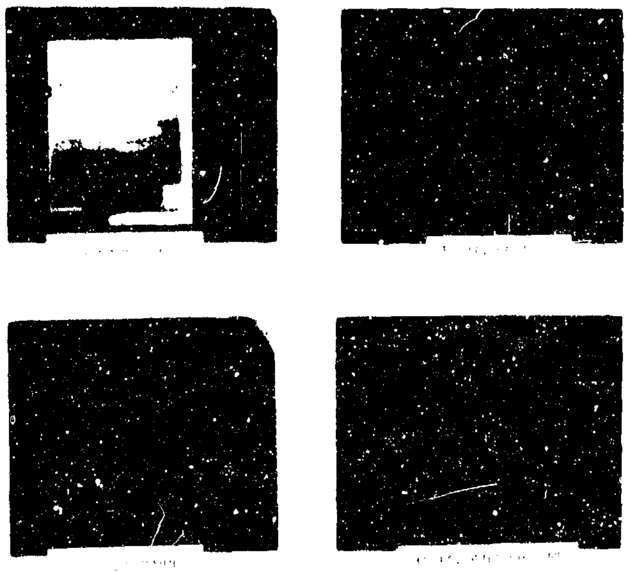


THERMAL IMAGE OF HEAT PENETRAMETER

FIGURE 4

After positioning the scanner in front of the CO_2 laser, beam alignment was achieved by viewing with the thermal imaging camera. This also served to determine the effects of the 30-watt laser beam on the specimen's surface. Figure 5 illustrates the laser beam striking a steel plate continuously for 30 seconds. The lateral dissipation of heat is seen as the steel is heated in the area of the beam.



1/16 INCH STEEL PLATE
19Ma-BEAM

EFFECTS OF CO_2 LASER BEAM STRIKING A STEEL PLATE

FIGURE 5

The difficulty in locating the moving laser beam with respect to the specimen made it necessary to provide a visual indicator of the beam position. Indicator lights were placed on the scanner control assembly to show the beginning of the scanning pattern in the upper left corner of the area to be illuminated. This allowed the initial position of the laser beam to be established before the laser was turned on and the specimen surface heated.

To provide some measure of the increase in surface temperature due to the scanning laser beam, a chrom-alumal thermocouple was fabricated and placed on the specimen's surface. The laser beam was then scanned across the junction and the temperature profile of the thermocouple at the specimen's surface was recorded. Figure 6 illustrates the thermocouple at the specimen's surface. Figure 7 is a recorder trace of the temperature increase in the specimen at the thermocouple junction as the laser beam crossed the specimen and returned to its starting position, thus striking the junction twice. The scanning beam at the laser-to-specimen distance of 43 inches made a two-pass scan in 9.0 seconds and traveled a total horizontal distance of 34 inches. By retracing its path in completing a horizontal scan, the laser beam imparted sufficient energy to raise the specimen's surface temperature by 18°.

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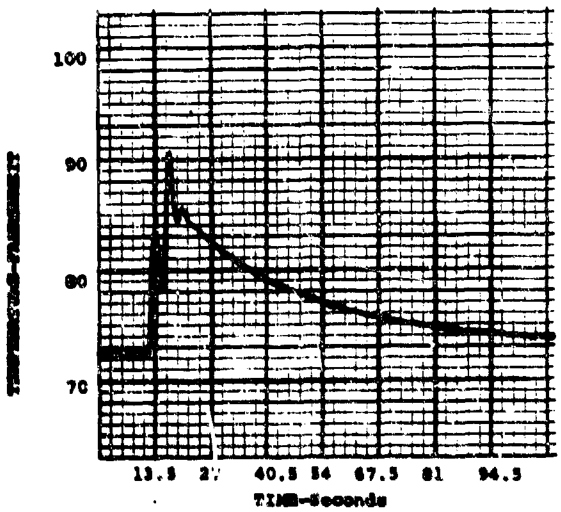
THERMOCOUPLE FOR SURFACE TEMPERATURE MEASUREMENT

FIGURE 6



COOLING CURVE OF THERMOCOUPLE AFTER TWO SWEEPS

FIGURE 7

RESULTS

A composite specimen was fabricated which consisted of:

Flat black enamel outer coating

1/32 inch stainless steel panel

Steel defcon adhesive

1/32 inch aluminum with one inch diameter hole

Steel defcon adhesive

1/32 inch stainless steel back panel

Figure 8 is a thermogram of the specimen in the passive mode of testing. The specimen had been heated with hot air and was cooling to room temperature. Figure 9 shows the same specimen as viewed in the active mode. The backing panel shows the effects of the scanning beam.

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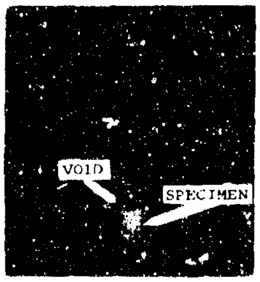
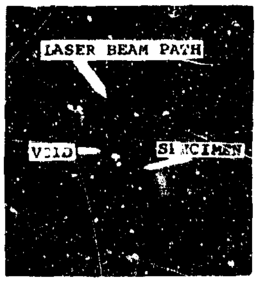


PASSIVE THERMOGRAM

BONDED STEEL SPECIMEN

FIGURE 8



ACTIVE THERMOGRAM

BONDED STEEL SPECIMEN

FIGURE 9

It can be seen that under the passive testing technique the void appears as a "cold" spot in the heated specimen. Under active illumination, the void appears "hot" to the thermal imaging camera while the remainder of the specimen has cooled to near ambient conditions. The resolution of the void under the active condition was superior. and the general shape and size could be determined. Under passive conditions, only the presence of a defect could be stated with any degree of certainty.

Prior to the application of a flat black enamel front surface to the composite specimen, the laser beam could not be located while traversing the specimen. Consequently, the defect could not be located. This was due to the high reflectivity of the polished stainless steel surface to the 10.6 micron laser radiation. Although a drawback to the use of the laser illumination technique on a routine basis, the problem is conveniently solved by the application of a coating which will absorb the laser radiation and hence emit efficiently.

Figures 10 and 11 illustrate a rubber bonded to aluminum specimen as evaluated by the passive and active techniques, respectively.

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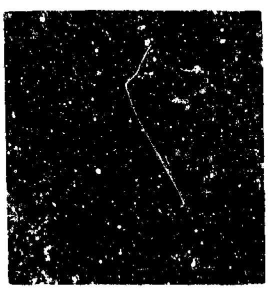
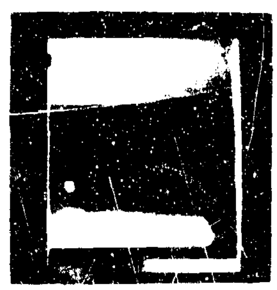


PASSIVE THERMOGRAM

RUBBER BONDED TO ALUMINUM

FIGURE 10



ACTIVE THERMOGRAM

RUBBER BONDED TO ALUMINUM

FIGURE 11

Again it is noted that two voids appear as "hot" spots under passive examination and as "cold" spots when scanned actively. In Figure 11, the scanning laser beam continues to irradiate the lower portion of the specimen. The defects in the central portion appear soon after the scanning beam has passed the area. Since the rubber front surface of the specimen has a high emissivity, it was not necessary to overcoat the specimen to absorb the laser beam efficiently. The defects in the specimen were detected under a wide range of laser scanning speeds and beam power.

A T136 Tank track shoe was selected as a typical bonded specimen having a relatively thick cross section. The track shoe consists of a formed steel plate approximately 3/16 inch thick to which a rubber pad is bonded. The rubber varies in thickness from approximately 1/2 inch on the edges to 1-11/16 inches in the central portion of the track shoe. When viewed in either the passive or active modes, results were inconclusive and non-reproducible. Although defects were known to exist in the specimens, it was not possible to accurately detect these areas. Figure 12 illustrates a passive thermogram of a heated track shoe. A portion of the difficulty in locating the disbond areas can be attributed to the irregular surface on the metal side of the track. On some specimen track shoes the metal surface was clear of any rubber. On other specimens, rubber had formed over a portion of the metal in an irregular pattern. Figure 13 illustrates the metal side of a track shoe with some build-up of rubber on the metal. The twin "hot" areas are due to metallic mounting bolts on the track shoe.

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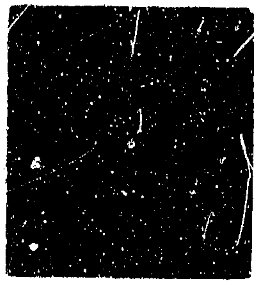

PASSIVE THERMOGRAM

TANK TRACK SHOE

FIGURE 12

PASSIVE THERMOGRAM

TANK TRACK SHOE

FIGURE 13

REFERENCES

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13. ABSTRACT

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